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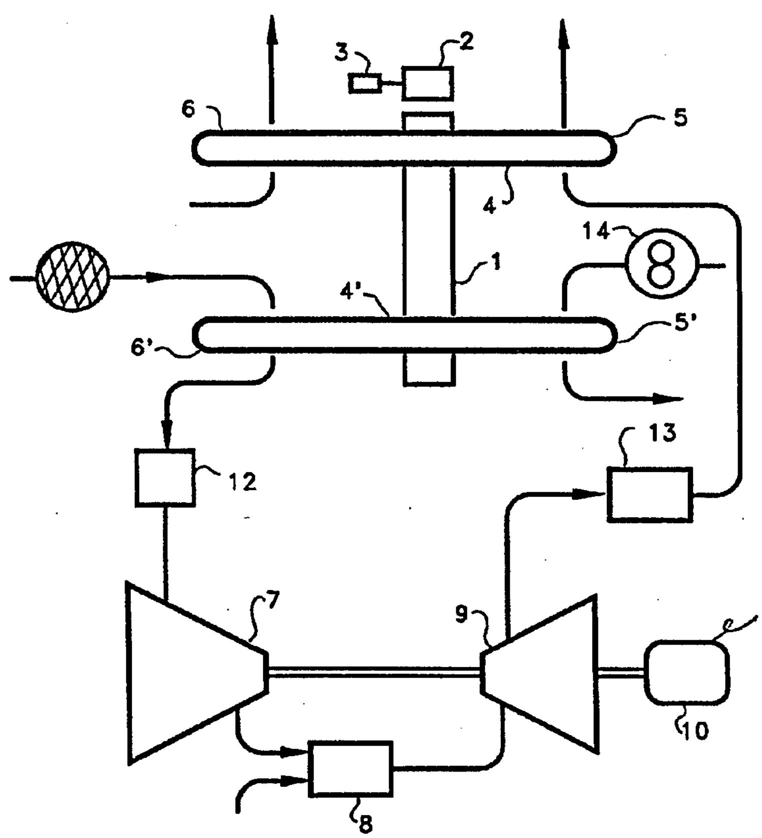
(54) Title: SORPTION COOLING OF COMPRESSOR INLET AIR

(57) Abstract

Compressor (7) inlet air is cooled by a sorption cooler (6') and hot depressurized gas is used to heat-activate the sorption cooler (5). Cooling compressor (7) inlet air by 30 °C increases throughput and decreases drive energy by about 10 %. Cooling combustion turbine (9) inlet air by 30 °C increases output by 20 % and reduces heat rate by 5 %. Referring to the figure, inlet air is cooled by a rotary multimodular sorption cooler (6') comprised of valveless modules (4). The sorption container (5) of each module (4) is heat-activated by hot depressurized gas from the turbine (9).



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Sorption Cooling of Compressor Inlet Air

Technical Field

The capacity and energy efficiency of air compression systems are increased by using a sorption apparatus to cool the compressor inlet air.

Background Art

Decreasing the temperature of air supplied to the inlet of an air compressor is known to provide the dual benefits of reduced energy consumption and increased compression capacity. Unfortunately the traditional method of cooling the air, by vapor compression refrigeration, introduces offsetting disadvantages. The required refrigeration energy completely negates the reduction in compression energy, and the required added capital for refrigeration equipment completely negates the advantage of higher compression capacity.

In recent installations, the capital necessary for refrigeration equipment has been substantially reduced via thermal storage, e.g. using large storerooms of ice. In this approach, the refrigeration system is sized for only about 20% of the full refrigeration duty. When cooling compressor air, the ice storage supplies most or all of the refrigeration duty. When the air compressor is not operating, the refrigeration system replenishes the ice.

That approach achieves the advantage of increased compression capacity, at a cost lower than simply adding more compressor. However it has the major disadvantages that the cooling is only available less than 20% of the time, and that there is no net energy saving. Due to those constraints it has only found application in conjunction with peaking combustion turbines for electric utilities.

One of the lowest cost and lowest energy ways of cooling compressor inlet air is by evaporative cooling. This approach relies on a significant difference between ambient wet bulb temperature and dry bulb temperature. It has the disadvantages that the amount of cooling available is usually small, and most importantly, can not be relied upon, owing to the dependence upon the vagaries of weather.

Proposals have been made to cool compressor inlet gas with an absorption apparatus. U.S. Patent 4936109 is one example. Frequently the heat content of the hot compressed gas is cited as the source of driving heat for the absorption apparatus. This approach has the advantages that a substantial degree of cooling is reliably available at all times, and the

compression energy savings is almost fully preserved. However it has the disadvantage that the capital requirements are typically substantially higher than for the vapor compression approach to refrigeration.

What is needed, and among the objects of this invention, are process and/or apparatus for cooling compressor inlet air which simultaneously achieves the low cost of vapor compression/ice storage systems, and the high energy efficiency of absorption systems driven by waste heat. It should reliably provide high levels of cooling all the time, rather than just at peak load periods on dry days, and it should approach the simplicity and compactness of the evaporative cooling systems.

Prior art disclosures of rotary multimodular intermittent sorption cycles include U.S. Patents 1,472,432; 4,169,362; 4,402,919; 4,574,874; 4,660,629; and 5,167,937. All disclose single effect cycles and use of solid sorbents. U.S. Patent 5,297,359 discloses a multiple-effect (trisorption) cycle in a rotary multimodular configuration.

Various stationary multimodular configurations of intermittent sorption cycles have also been disclosed: U.S. Patents 1,566,531; 1,790,757; 4,327,376; 4,623,018; 5,046,319; and Russian Patent 832270 (1979).

Disclosure of Invention

In one aspect this invention applies a known apparatus - a multimodular rotary sorption cooler adapted for direct contact heat exchange with air - to a new use: cooling compressor inlet air. In a further aspect it discloses a fully integrated arrangement wherein heat from the process using the compressed air is recycled to activate the sorption apparatus. That embodiment extends to all known sorption cycles, not just the multimodular ones.

A heat activated sorption apparatus requires four separate exchanges of heat with heat transfer fluids: high temperature heat input to the generator (desorber), low temperature heat input to the evaporator, and medium temperature heat rejection from both the condenser and absorber. The process disclosed herein for achieving the low capital cost objective for compressor inlet air cooling is to conduct as many as possible of those four heat exchanges, (preferably all of them) directly and at ambient pressure. Directly means without a separate intervening heat transfer fluid. An example of indirect heat exchange is cooling a cold brine with the sorption apparatus evaporator in a first heat exchanger and then using the cold brine to cool the

inlet air in a second heat exchanger. The requirement for two separate heat exchangers adds undesirably to the cost.

The intermittent sorption cycle comprises two separate and distinct operating modes: generate-condense, and absorb-evaporate. There is also necessarily a brief interval between modes when the temperatures and pressure adjust to the opposite mode.

In the multimodular embodiment, this disclosure explicitly extends to the use of liquid sorbents in the modules, either in addition to or in lieu of solid sorbents. In some embodiments liquid sorbents provide distinct advantages - both better heat and mass transfer coefficients, and also higher COPs. The disclosure also extends to the use of multi-effect multimodular sorption cycles, both rotary and stationary, in the disclosed application of compressor inlet air cooling.

This disclosure also extends to staging two or more multimodular groupings or tiers in sequence, i.e. providing for series air flow across the tiers. This allows the individual modules to operate at lower lifts (and hence more efficiently) while simultaneously achieving larger temperature changes in the respective air streams.

In the multimodular embodiments, the disclosure extends to any means for alternating the modules between generate-condense mode and absorb-evaporate mode: e.g. use of valves, or for the case of valveless hermetic modules, moving the modules past fixed air ducts, or even moving sections of movable duct relative to fixed modules. The relative motion may be smooth and continuous or intermittent, and may be linear or rotary. The preferred means of accomplishing the relative mothion is to mount the modules in a rotatable cylindrical configuration with hollow interiors, and rotating that configuration relative to four segments of fixed ducting, one for each air or gas stream. This provides a particularly compact and economical means of achieving the required gas phase heat transfer, by permitting short and direct paths for heat exchange contact.

In the multimodular embodiments, this invention extends to a configuration wherein the number of modules in the absorb-evaporate mode is substantially larger than the number in the generate-condense mode. Prior art multimodular arrangements have the same number in each mode. However the absorb-evaporate mode has been found to be kinetically more limiting than the other mode, and hence the unequal arrangement provides for more effective and economical use of the available heat transfer surface. For example, Figure 3 illustrates 9 modules aligned with collection plenum 27, i.e.

in the evaporate-absorb mode, and only 5 modules aligned with plenum 30, in the condense-generate mode.

In the multimodular embodiments, the invention extends to the practice of evaporatively cooling one or both of the cooling air streams supplied to the modules, thus achieving higher lift and/or lower flow of cooling air.

The modules may contain a refrigerant plus one or more sorbents. Alternatively, "resorption" modules can be used, in which a sorbent replaces the liquid phase refrigerant, and is paired with a different (higher lift) sorbent.

Brief Description of the Drawings

Figure 1 is a schematic simplified flowsheet which illustrates a rotary sorption cooler integrated with a combustion turbine, wherein the sorption cooler has only a single tier of modules.

Figure 2 provides constructional details of the sorption cooler, and Figure 3 is a cross-section of Figure 2.

Figure 4 is a schematic of a two-tier sorption cooler integrated with an industrial process using an air compressor.

Modes for Carrying out the Invention

Referring to Figure 1, a rotary mounting frame 1, caused to rotate by gear 2 and drive motor 3, has mounted on it a plurality of valveless hermetic sorption modules 4, 4'. Each module is comprised of a section or compartment (5,5') containing a sorbent, connected to a separate cooling compartment (6,6'). In one embodiment the cooling compartment contains a refrigerant capable of being absorbed and desorbed by the sorbent. In another embodiment the cooling compartment contains a different sorbent having lower affinity for the refrigerant.

When water is the refrigerant, the cooling compartment contains water. When hydrogen is the refrigerant, the cooling compartment contains a hydride, different from the hydride in the sorbent compartment. When ammonia is used, which along with water is one of the two preferred refrigerants, the cooling compartment can contain either liquid ammonia or an ammonia chemisorbent. Other common refrigerants can also be used, such as CO_2, SO_2, methanol, methane, other hydrocarbons, and hydrocarbon derivatives (e.g. HFCs).

Either liquid or solid sorbents can be used, and the latter can be physisorbents or chemisorbents. Liquid sorbents for water include the lithium halides, the alkali metal nitrates including mixtures thereof, and the alkali

metal hydroxides including mixtures thereof. Physisorbents for water and for ammonia include molecular sieves, activated carbon, activated alumina, and silica gel. Chemisorbents for water and for ammonia include the alkaline earth halides and the transition metal halides. Water is a liquid sorbent for ammonia.

Some of the modules (4) are in the generate-condense mode and the others (4') are in the evaporate-absorb mode. Rotation of mount 1 causes the various modules to alternate between modes, in offset pattern whereby cooling is continuously produced.

A combustion turbine comprised of compressor 7, combustor 8, turbine 9, and generator 10 receives cooled air from the sorption cooler. Air is filtered in filter 11 and then directly cooled by the cooling containers 6' of modules 4'. The cooling will usually also dehumidify the air and leave it saturated with moisture. If cooled below 3°C, there is a possibility that ice will form in the compressor inlet ducting (the "bellmouth"), and further that chunks of ice could occasionally dislodge and damage the rapidly rotating turbine blades. In order to protect against that, a means for icing protection 12 is provided. This may consist of heaters for warming the bellmouth, or injectors for injecting a small amount of warmer and/or dryer air at the air flow boundary. A particularly advantageous means for icing protection is an induced draft fan, which overcomes the pressure drop through the sorption cooler plus associated capacity decrease.

After the cooled air is compressed, combusted, and work expanded in the combustion turbine, the hot depressurized exhaust is used to power the sorption cooler. When appropriate, it can also supply heat to a heat recovery steam generator 13. In either case, it directly heats the sorbent containers 5 which are in the generate mode. Cooling air is supplied to provide direct cooling to condensation zones 6 and absorption zones 5', e.g. by air fan 14.

Figure 2 illustrates details of the fixed ducting and its relationship to the rotating member of the sorption cooler, and Figure 3 is a cross-section of one part of Figure 2. The rotating member is as previously described - it consists of mount 1, drive gear 2, drive motor 3, and a plurality of modules 4,4'. Each module includes a cooling section 6,6', and a sorbent section 5,5'. The cooling sections may contain a liquid phase refrigerant, in which case it is advantageous to include a wick or foam material to hold the liquid against the module walls. Alternatively it can contain a different sorbent, having lower refrigerant affinity. Additional details of the rotating member are fins 16 to

enhance air side heat transfer; barriers 17 to prevent migration of condensed phase material; and baffles 23 separating the individual modules.

The fixed structure portion of the sorption cooler is comprised of the mounting, bearing, and sealing assembly 33. The remaining fixed structure is ductwork which divides the module sections of each end of the rotating member into two gas separate flow paths. On the cooling end, fixed ductwork is inserted into the hollow interior of the ring of modules. Divider 15 separates the cooling air side plenum 20, from the plenum for air being cooled 22. Perforated plate or screen 21 admits cooling air to contact with the module sections 6 in the upper arc, and thence into external duct plenum 30, exiting through duct 32. The air being cooled enters plenum 22 from duct 28, contacts module sections 6', is collected in external plenum 27, and exits via duct 29. Similarly on the hot or sorbent side, fixed plenums 34 and 26 divided by divider 25 are inserted into the hollow interior. Hot depressurized gas enters plenum 34 from duct 19, contacts module sections 5 in the upper arc, and then is exhausted via the external plenum and stack 18. Cooling air supplied to plenum 26 cools the module sections 5' which are absorbing refrigerant from evaporating sections 6'.

In order to prevent mixing of different temperature gas streams, dividers 15 and 25 separate the gas streams while in the interior plenums. Also, fixed baffles 35 separate the gas streams in the exterior plenums e.g. 27 and 30. The dividers and fixed baffles work in conjunction with the moving baffles 23 to minimize mixing of different temperature air streams. Since all the air streams are close to atmospheric pressure, the baffles are of simple construction and do not require precise tolerances.

Figure 4 illustrates a more advanced sorption cooler having a two tier module arrangement, as applied to a generic industrial process using an air compressor. It also illustrates that the modules can be mounted vertically as well as horizontally. Mounting ring 41 has affixed to it two rings of modules, 43 and 44. The entire assembly is caused to rotate about vertical axis 42 by drive gear 45 and drive motor 46. Cooled inlet air is supplied to compressor 47, powered by prime mover 48. Compressed air is supplied to process 49. If the process exhaust product is appreciably above atmospheric pressure, it is work expanded in expander 50.

As in Figure 1, Figure 4 has four gas flows to the sorption cooler: the air being cooled (51), the hot gas (52), and two streams of cooling air (53,54). The primary difference from Figure 1 is that each gas stream contacts two tiers of module sections in series. Also, the flow to the same modules are

countercurrent, e.g. cooling stream 54 contacts module 44 first, then module 43, whereas stream being cooled 51 contacts module 43 first, then module 44, i.e. the reverse order. Also, cooling stream 54 is advantageously precooled by evaporative cooler 55 before cooling the modules.

As a numerical example of the use of this invention and comparison between the Fig. 1 and 4 embodiments, consider an ambient temperature of 35°C, and a sorption cooler designed to lower the inlet air temperature to 5°C. If a minimum 10°C approach temperature is desired for all heat exchangers, then the cooling containers must operate at -5°C. Assuming a 20°C rise in the cooling air temperature, the absorption steps have a maximum temperature of 65°C. For the cycle lift of 70°C, the NH_3-activated carbon sorbent working pair has a COP of about 0.3. With the inlet air cooled by 30° C, the hot gas must be cooled by 30°C ÷ COP, or 100°C, and its final temperature needs to be approximately 200°C due to the characteristics of the NH_3-AC pair. Hence hot gas supply is about 300°C. Similarly, the total quantity of cooling air required can be calculated as [30 x 1.3] ÷ [20 x 0.3] = 6.5 times the amount of inlet air.

If evaporative cooling is used to cool both cooling air streams by 10°C, whereby they pick up 30°C of temperature vice 20°C, the required cooling air flow reduces by one third, to 4.3 times the inlet air flow.

For the two tier embodiment, only the colder tier evaporators operate at -5°C, and the warmer tier evaporators at about 10°C. Thus water refrigerant can be used in the warmer tier. Using evaporative cooling of the cooling air, and allowing it to heat up by 40°C, implies a 45°C air temperature leaving the colder tier absorbers, and 65°C leaving the warmer tier absorbers. Thus the ammonia-AC pair must provide a lift of 60°C, where the COP is 0.33, and the water-zeolite pair provides a lift of 65°C, at a COP of 0.37. Based on the average COP of 0.35, the temperature level and drop required of the hot gas are decreased, and also the cooling air decreases to [30 x 1.35] ÷ [40 x 0.35] = 2.89 times the inlet air flow. It will be understood that a third tier would correspondingly yield further advantages.

Although only single-effect multimodular sorption cycles are illustrated in the figures, it will be understood that any known multi-effect cycles can be substituted therefor without departure from the spirit of the invention. Use of some pairs and/or cycles results in quite low exit temperatures of the hot gas, e.g. below 100°C. This can be of added benefit due to recovery of valuable water content from the hot gas. Water recovered from the cooled inlet air and/or from the hot gas can be used to supply the evaporative cooler.

Industrial Applicability

Most compressor types are mass flow limited devices, and hence will benefit from the capacity increase which lower temperature inlet air provides. All mechanical compressors conform to the thermodynamic laws of compression, and hence will realize a reduction in mechanical drive energy due to inlet air cooling. Specific examples of devices or processes having an air compressor and which will benefit from this disclosure include combustion turbines, reciprocating engines, and industrial processes using compressed air such as natural gas reformers, fluidized catalytic cracker regenerators, cryogenic air separation units, nitric acid plants, Claus plants, ammonia synthesis plants, and blast furnaces.

Claims

1. A heat activated sorption apparatus for cooling the air supply to an air compressor to below ambient temperature comprising:

a) multiplicity of valveless hermetic sorption modules, each comprised of a generator/absorber section containing a sorbent and a condenser/evaporator section containing a refrigerant;

b) a sequencing mechanism which sequences said modules intermittently between generate-condense and evaporate-absorb mode, whereby at any time a predeterminable portion of said modules are in the latter mode, and the refrigerant contained in the condenser/evaporator sections of those modules is evaporating;

c) inlet air ducting which routes said compressor inlet air in heat exchange contact with the condenser/evaporator sections of said modules which contain evaporating refrigerant.

2. Apparatus according to claim 1 wherein said means for sequencing is comprised of a means for effecting relative motion between said multiplicity of modules and said inlet air ducting.

3. Apparatus according to claim 1 wherein said modules are affixed to a mounting structure which is adapted for rotation, and said inlet air ducting is stationary.

4. Apparatus according to claim 1 wherein said modules are arranged in two tiers adapted for sequential contact of said air.

5. Apparatus according to claim 4 wherein the sorbent in the modules of one tier is different from the sorbent in the modules of the other tier.

6. Apparatus according to claim 1 additionally comprised of a combustion chamber for compressed air from said compressor, a work expander for depressurizing and extracting work from hot combustion gas from said combustion chamber, and gas ducting which routes depressurized gas from said work expander to heat exchange contact with the generator/absorber sections of the modules which are in the generate-condense mode.

7. Apparatus according to claim 1 additionally comprised of vent ducting for a vent gas comprised of a major proportion of steam which routes said vent gas to heat exchange contact with the generator/absorber sections of the modules in the generate-condense mode.

8. Apparatus according to claim 1 additionally comprised of a means for providing cooling air to at least one of the generator/absorber sections of the modules in the evaporate-absorb mode and the condenser/evaporator sections of the modules in the generate-condense mode.

9. The apparatus according to claim 1 wherein said sorbent is a liquid

10. In an apparatus comprising an air compressor, a combustion chamber in which compressed air is reacted with a combustant to become a hot pressurized combustion gas, and a work expander for depressurizing combustion gas and producing work, the improvement comprising:

a) a sorbent-refrigerant pair;

b) a container for said sorbent which is adapted for alternately being heated by depressurized combustion gas from said expander and then being cooled by ambient air;

c) a containment for said refrigerant which is adapted for alternately being directly heated by the air supply to said compressor and then being cooled by ambient air;

d) a fluid connection between said containment and said container.

11. The apparatus according to claim 10 comprised of a multiplicity of hermetic sorption modules, each comprised of one of said containers and one of said containments.

12. The apparatus according to claim 11 comprised of a motion mechanism which causes relative motion between said modules and said respective air and gas streams, whereby said alternating coolings and heatings are effected.

13. The apparatus according to claim 11 comprised of fixed ducts for said respective gas and air streams, plus a rotatable mounting for said modules, whereby rotation of said mounting for said modules relative to said fixed ducts causes said alternation.

14. The apparatus according to claim 11 wherein said modules are arranged in at least two tiers, whereby each air and gas stream contacts at least two module containers or two module containments in series flow.

15. The apparatus according to claim 11 wherein the refrigerant-sorbent pair in the modules of one tier is different from the pair in the modules of another tier.

16. The apparatus according to claim 11 wherein said sorbent is a solid.

17. The apparatus according to claim 11 wherein said sorbent is a liquid.

18. A process for cooling compressor inlet gas to below ambient temperature prior to compression comprising:

a) providing a plurality of modules, each module containing a sorption working pair, a sorbent compartment, and a cooling compartment;

b) in a first step, heating the sorbent compartment above 90°C, and cooling the cooling compartment with ambient air;

c) in a second step, cooling the sorbent compartment with ambient air, and contacting the compressor inlet gas with said cooling compartment, whereby said gas is cooled by at least 20°C;

d) alternating steps b) and c) in an offset pattern for the various modules, whereby continuous cooling is provided.

19. The process according to claim 18 additionally comprising evaporatively cooling the ambient air supplied to said cooling compartment in step b).

20. A process for cooling compressor inlet air to below ambient temperature comprising:

a) cooling said inlet air by directly exchanging heat with at least one of

i) an evaporating refrigerant

ii) a low lift sorbent of refrigerant which is desorbing;

b) absorbing the refrigerant vapor from step a) into a high lift sorbent;

c) compressing the cooled air from step a);

d) supplying the compressed air from step c) to an industrial utilization process;

e) returning a hot depressurized gas from said industrial utilization process; and

f) exchanging heat from said hot depressurized gas to said high lift sorbent.

21. The apparatus according to claim 20 wherein said sorbent is a solid.

22. The apparatus according to claim 1 wherein the number of modules in the evaporate-absorb mode exceeds the number in the generate-condense mode by at least three.

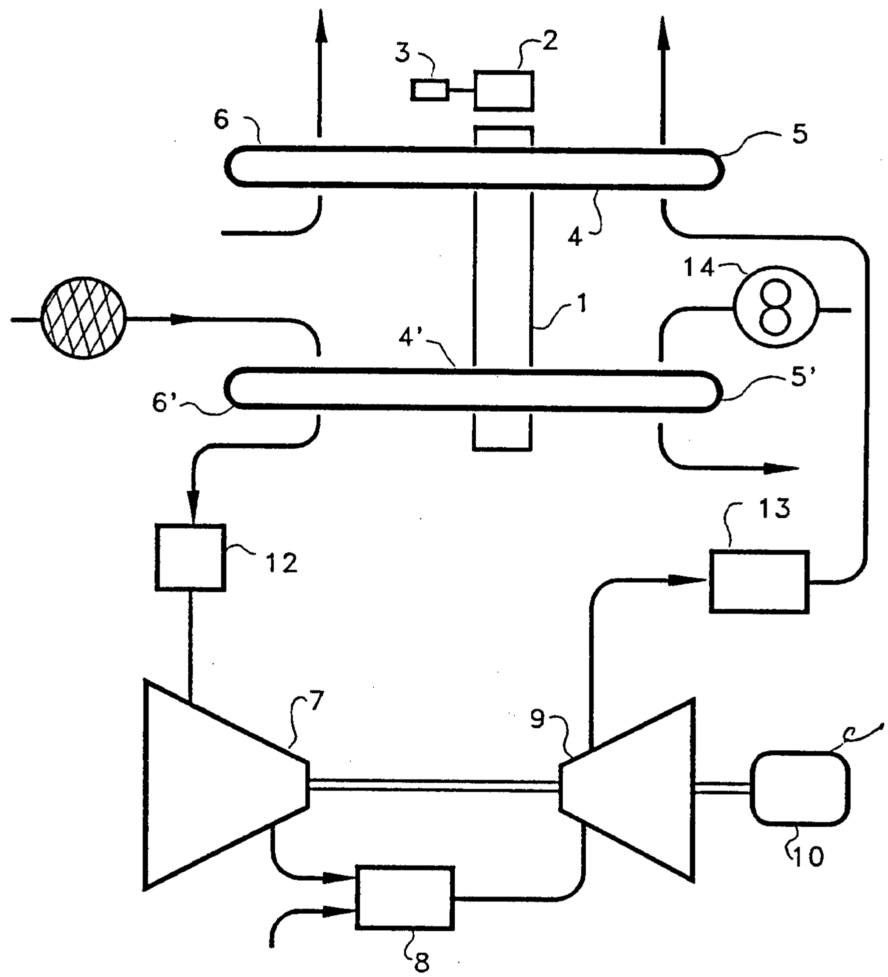

FIG. 1

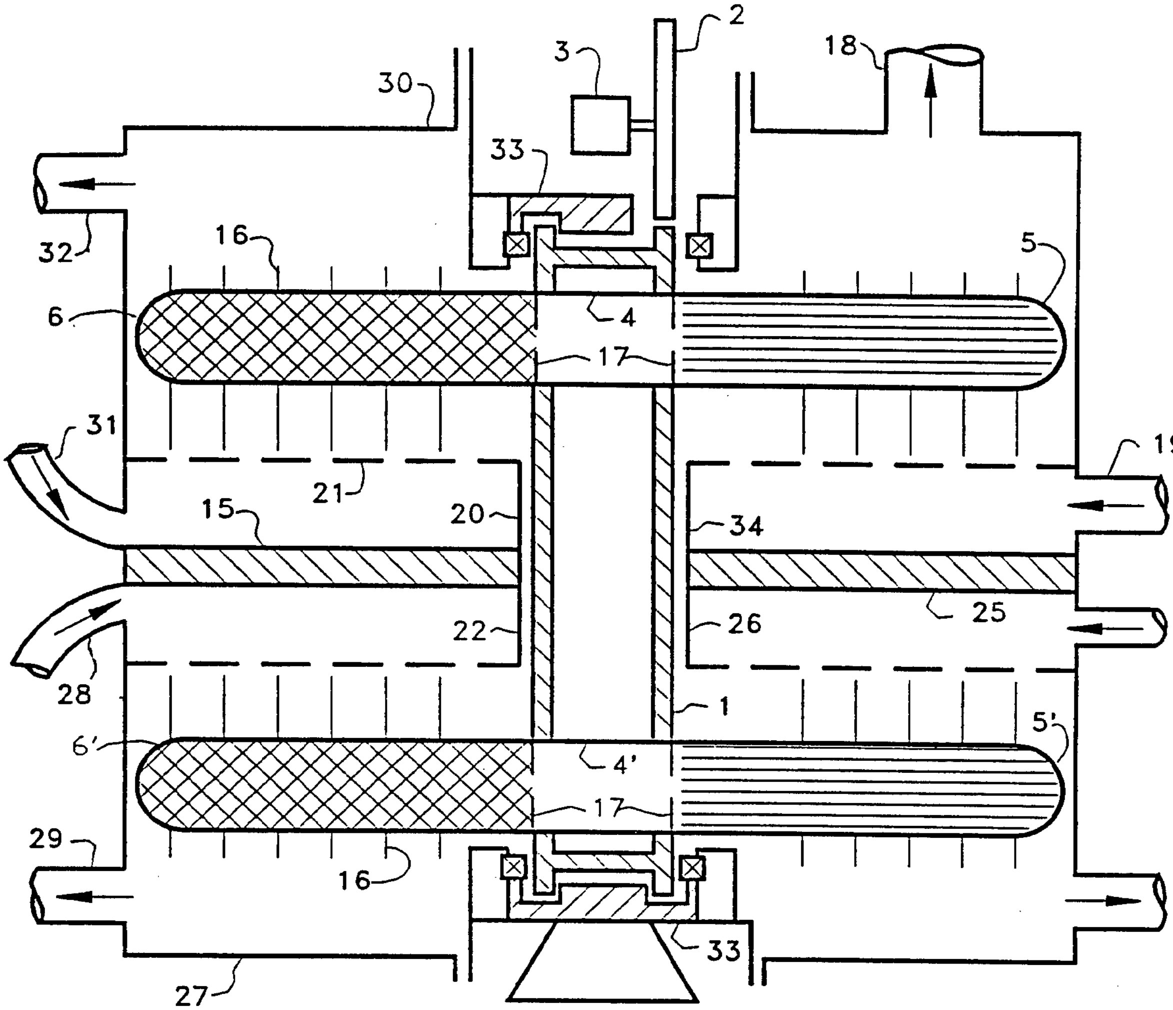
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FIG. 2

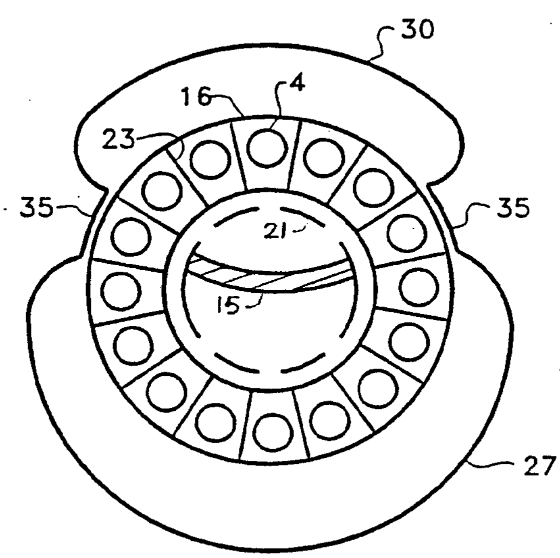
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FIG. 3

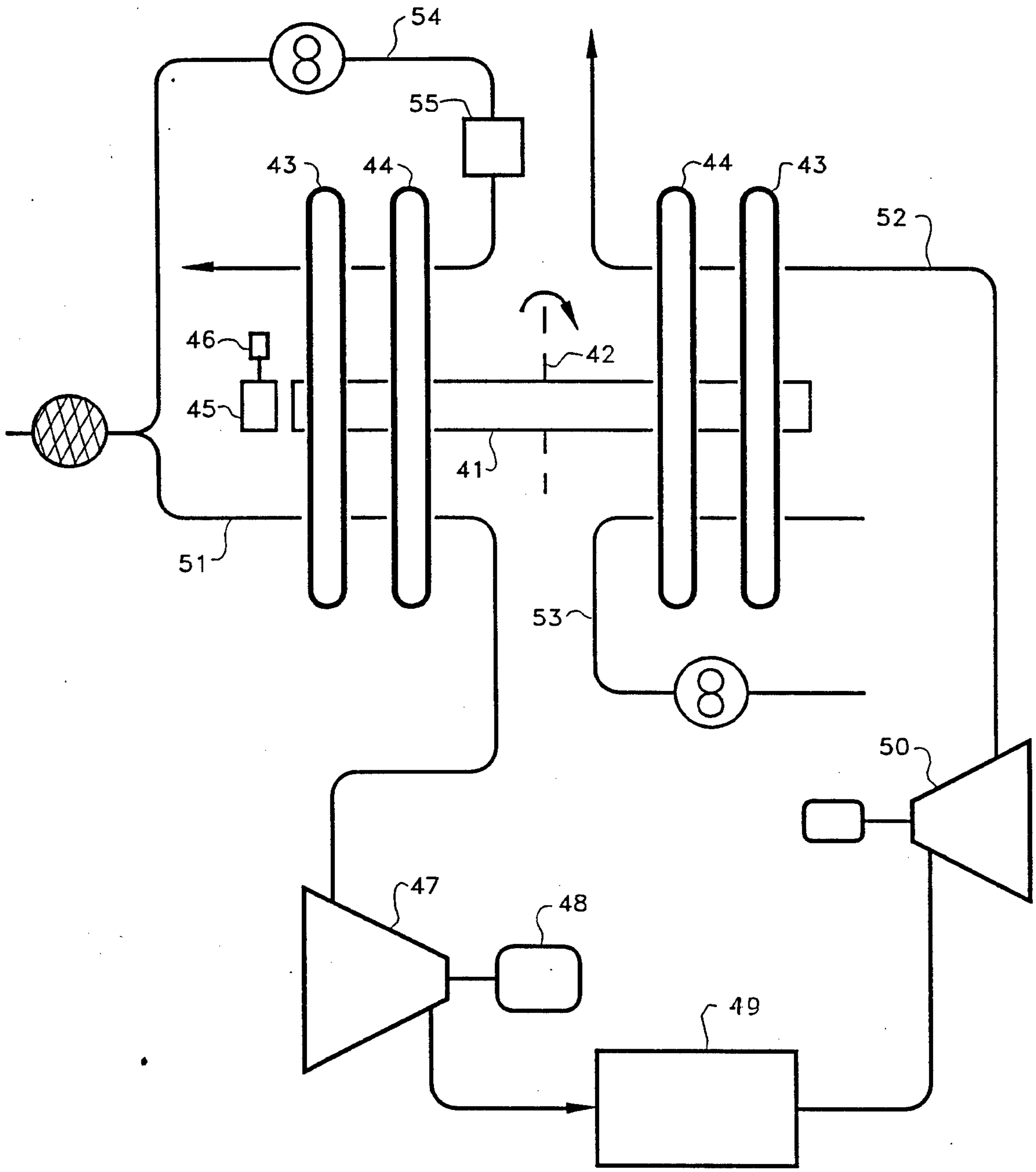

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/05337

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :F25B 17/08
US CL :62/480, 477, 402; 165/104.12
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 62/480, 477, 402, 478, 94, 101, 112, 271; 165/104.12; 60/39.511, 39.512, 728

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US, A, 4,866,947 (WEBSTER) 19 September 1989.	1, 10, 18, 20

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/05337

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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